Modular And Multifunctional Systems in the New Millennium Program

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ABSTRACT

NASA's vision for science exploration in the next century is based on frequent, affordable missions enabled by small, low-cost autonomous spacecraft. Through the New Millennium Program (NMP), NASA is establishing a new and highly integrated approach to developing and flight-validating technologies that meet these goals. Enabling the mission scenarios envisioned and the overarching goal of reducing life-cycle costs presents significant challenges across all aspects of spacecraft design, implementation, and operation.

The NMP has identified Modular and Multifunctional Systems (MAMS) technologies as addressing key capability needs for the new millennium. MAMS technologies fall into four general categories: i) materials and structures, ii) power and propulsion, iii) planetary surface interface systems, and iv) *Process Millennia*, our term for advanced computer-aided engineering design tools, development methods, and environments. The MAMS team has developed specific technology road maps and plans for each of these four technology areas. This paper describes these technologies and outlines our plans for their flight validation.

Our technologies help to fulfill NASA's 21st century mission needs in different but synergistically supportive ways. For example, propulsion and power systems that deliver high specific energy and high specific power at low cost will provide NASA with rapid access throughout the solar system. Advanced materials and structures that deliver low mass, low cost, and low launch volume will allow microspacecraft to deploy large-diameter apertures with good surface precision improving power collection, thermal control, communications, and science instruments thereby reducing the cost and mass of new millennium spacecraft. Advanced in situ science and sample return missions will be made affordable by planetary surface interface systems that provide low cost approaches to sample acquisition and retrieval and low cost carriers for the new generation of in situ science instruments. Finally, Process Millennia will enable the New Millennium vision of fleets of highly capable spacecraft affordably revolutionizing NASA's space science program by tying together all the technologies of the New Millennium to reduce development cycle time and cost while increasing system performance and reliability.

I. INTRODUCTION AND OVERVIEW

As described in references 1 and 2, the New Millennium Program (NMP) has been established to accelerate the infusion of breakthrough technologies into NASA space science missions. The goal of this technology infusion is to fulfill the NASA vision of frequent, low-cost missions to deep space and to planet Earth. The NMP is organized into Integrated Product Development Teams (IPDTs) and Flight Teams. IPDTs have the role of identifying and prioritizing candidate technologies for validation by the New Millennium Program and developing technology road maps or long-range plans of how the technologies will be infused into NASA space science missions. Flight Teams execute missions to validate these technologies by incorporating them as functional subsystems, components, or experiments.

Three of the NMP missions will be deep space planetary missions and three will be Earth orbital. Missions are designated DS-1 through DS-3 and EO-1 through EO-3 where DS stands for deep-space and EO stands for Earth orbital. For a preliminary description of these missions see reference 3. Reference 2 includes a description of the process whereby technologies are selected for a given mission and provides an overview of the NMP.

The present paper addresses the technologies under consideration by the Modular and Multifunctional Systems (MAMS) IPDT and the role of the team. To this end, Section II describes the technical charter of the MAMS IPDT and its membership. The next four sections of the paper provide a technical description of the four major technology areas the MAMS team is working in. For example, Section III, *Breakthroughs in Space Structures*, describes the materials and structures technology the MAMS team has identified as promising the low mass, low cost, and low launch volume required for typical 21st century space missions. These structures will reduce the mass of spacecraft and enable the development of apertures that are large in area, possess good surface precision, and are compatible with small spacecraft launched by small rockets. Applications of these apertures include power collection, thermal control, telecommunications, and science.

Section IV, *Breakthroughs in Propulsion and Power*, describes technologies that deliver high specific energy and specific power at low cost. These technologies are critical to enabling the New Millennium goal of providing rapid access throughout the solar system for low-cost microspacecraft. Section V, *Planetary Surface Interface*, addresses the problem of enabling low-cost access to the surface of small bodies or planets. These technologies are critical to the vision of affordable sample return missions. Advanced computer-aided engineering design tools, development methods, and environments that reduce development cycle time and cost while increasing system performance and reliability is the subject of Section VI, *Process Millennia*.

The *Summary and Conclusions* section provides a top level overview of the MAMS team's technology road maps and a summary of the team's status in implementing our road maps.

II. MAMS IPDT TECHNICAL CHARTER AND MEMBERSHIP

The technical domain of the MAMS team includes those areas of engineering and technology that affect the performance of space flight systems in terms of energy, aperture, information, or payload fraction. In addition, we are responsible for ensuring that the NMP develops or utilizes the best possible tools and methods that can reduce 21st century program cost, mission development time, and/or risk. Figure 1 is a Venn diagram that attempts to capture the spirit of our charter. In Figure 1 *D* is data, *R* is risk, and *t* is time.

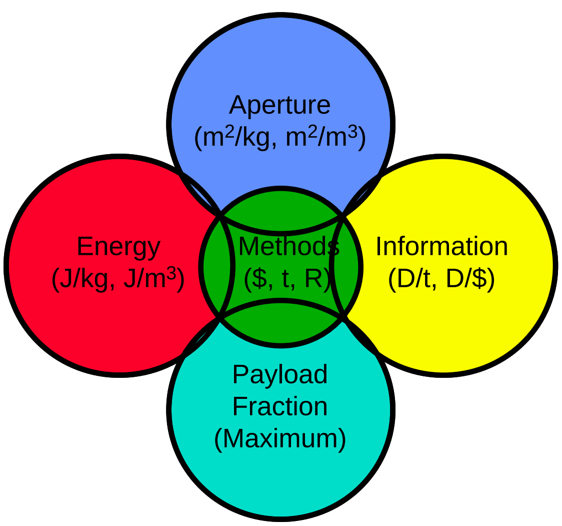

Figure 1 - Conceptualization of MAMS Team's Technical Charter

We chose a Venn diagram to depict our charter because it communicates the interdependency of each of these areas. For example, if we develop and validate a technology that allows the figures of merit for spacecraft apertures to improve —say by reducing mass, package volume, or cost— this will by necessity improve the figures of merit in the areas of energy and information. This is because a better collecting aperture will allow solar concentrators to weigh less and will therefore increase the specific energy or specific power of the spacecraft power system. If the same improvement in structures technology can be applied to radio frequency telecommunications antennas, more information can be sent back from the spacecraft faster, or at a reduced cost to the Deep Space Network.

This said, let us now consider each of the five technical areas covered by the MAMS charter. Starting at the top of Figure 1, the term *aperture* refers to spacecraft surfaces that collect, focus, reflect, or transmit radiation. These can be antennas, solar collectors, diffraction limited optics for science instruments, thermal radiators, sun shields, or photon buckets that concentrate but do not focus radiation. The figures of merit for these types of apertures are surface precision, reflectivity and absorbtivity, mass per unit deployed area, and packaged volume per unit deployed area. We intend to tackle head-on the fundamental question regarding apertures for small spacecraft, "given that the laws of physics relate the performance of many space systems to aperture diameter, how can spacecraft of the 21st century be lighter and cheaper than today's spacecraft without sacrificing performance?" We believe the answer to this question lies in part in improving the figures of merit of our apertures through the application of breakthrough technologies in materials, structures, and mechanisms.

Moving to the left in Figure 1 we encounter the area of energy. The MAMS team is concerned with two kinds of energy, electrical and orbital. The challenge with electrical energy is to provide low-cost, high-performance power for spacecraft operating throughout the solar system. This is especially critical for deep space missions where solar intensity at large distances from the Sun drops to tiny fractions of the solar intensity at the Earth's distance from the Sun. To keep cost down, we would like to minimize or eliminate the use of expensive radioisotope fuels.[4]

If we can develop very low-cost yet high-performance solar power technology, we can use electric propulsion to improve performance in the area of orbital energy. Studies have shown that electric propulsion can allow small spacecraft to explore the entire solar system faster and at a fraction of the cost of conventional deep space transportation systems.[4,5,6] Electric propulsion is therefore a critical focus of the MAMS team. However, even with a fully developed electric propulsion technology, there will still be a need for conventional chemical propulsion. For this reason we are also working on a very low-mass, low-cost modular chemical propulsion technology.

Many people believe that some function of cost, schedule, risk, and technical performance represents an envelope across which a project or mission manager cannot travel. Said another way, "you can't improve on cost, schedule, risk, and technical performance at the same time." We believe this perspective is wrong. Effectively used, it is obvious that today's engineering tools can allow us to work better, faster, and cheaper simultaneously while building projects that are less risky than we could with the engineering tools of a decade, or even a year ago. The challenge is to identify or develop the best tools for the job, create an environment where engineers and scientists can work together effectively as a team, and design processes that make the best possible use of these people, tools, and environments. We are facing this challenge with an activity we call *Process Millennia*. Process Millennia is central to our team's thinking and is called out as "Methods" in Figure 1.

We are pursuing advancements in the areas of aperture, energy, and methods primarily because of their benefits in information return and payload fraction. Payload fraction is defined as the ratio of the payload mass to that of the total flight system mass. It is not unusual for space science missions, especially planetary deep space missions, to posses payload fractions of only a few percent.[7,8,9] This is true because of the large post injection delta-Vs typically required for planetary missions and because the flight systems have to operate at highly variable distances from the Earth and Sun. Through developments in the MAMS technology areas we intend to dramatically increase payload fraction, which will increase the cost effectiveness of space science missions directly by reducing launch costs and indirectly by reducing development costs. In this way we will allow NASA missions to obtain more science information and return it to the Earth faster and less expensively.

TEAM COMPOSITION

Eleven team members and two co-leads comprise the MAMS team. Each member represents his home institution and its capabilities but each brings his own expertise and experience to the team process. Among the MAMS team members we have well over 200 years of scientific and engineering experience, 10 Ph.D.'s, three professors, and four senior corporate executives. The judgments contained in this paper were developed by this team working collaboratively over the past several months. Team members and their affiliations are listed here:

Joel Sercel, Team Co-Lead
Jet Propulsion Laboratory
California Institute of Technology

Brantley Hanks, Team Co-Lead
NASA Langley Research Center

William Boynton, Planetary Surface Interface
University of Arizona

Costa Cassapakis, Inflatable Structures
L'Garde Inc.

Edward Crawley, Process Millennia
Massachusetts Institute of Technology

Michael Curcio, Advanced Silicon Carbide
SSG, Incorporated

Alok Das, Spacecraft Bus Technologies
USAF Phillips Laboratory

William Hayden, System Applications
NASA Goddard Space Flight Center

David King, Propulsion
Olin Aerospace Company

Lee Peterson, Precision Deployables
University of Colorado

Suraj Rawal, Multifunctional Structures
Lockheed Martin Astronautics

Thomas Reddy, Energy Storage
Yardney Technical Products

Joseph Sovie, Power Systems
NASA Lewis Research Center

III. BREAKTHROUGHS IN SPACE STRUCTURES

The MAMS team has identified several materials, structures, or mechanisms technologies that have great promise for delivering lower mass, lower cost, and lower launch volume space systems for the new millennium. These structures will reduce the mass of 21st century spacecraft and enable the development of apertures that are large in area while retaining good surface precision. Applications of these apertures fall into the areas of microspacecraft power collection, thermal control, telecommunications, and science instruments.

Specific technologies the MAMS team is working on in this area include Multi-Functional Structures (MFSs), advanced forms of silicon carbide (SiC), precision deployable structures, and inflatables. MFSs are a breakthrough combining electronics packaging with power and data distribution. Advanced forms of silicon carbide represent an exciting possibility for higher levels of structural integration on 21st century spacecraft. Precision deployable structures have the long range potential to enable Hubble telescope scale optics to be incorporated into satellites launched on Pegasus-class rockets. Finally, precision inflatable structures represent a major breakthrough in deploying high quality apertures for solar power collection, antennas, sun shields, and radiators.

MULTIFUNCTIONAL STRUCTURES

NASA's vision for the 21st century includes the launch and operation of large numbers of low mass, low cost space assets. The fulfillment of this vision calls for an order-of-magnitude reduction in flight system mass relative to current spacecraft designs. Concentrating solely on structural mass reduction will not meet this need because structure typically represents as little as 10-15 percent of total system mass.[7] Miniaturization of avionics per se further reduces mass, but not the large parasitic mass associated with avionics containers, cables, structural support of packaged avionics, or connectors. These parasitic components can contribute as much as 50 percent of the mass of space science spacecraft.[8,9]

The solution to this dilemma can be found in MFSs, a new approach to electronics packaging, interconnect, and data & power distribution which integrates these functions with those of bearing mechanical loads and providing thermal control. The MFS concept involves embedding passive electronic components within the actual volume of composite materials, using new approaches to attaching active electronic components directly to mechanical surfaces, and using surface areas for mounting sensors and transducers.

MFS offers inherent modularity and directly incorporates functions such as data transmission, thermal control, and power distribution into structural panels. In so doing, it eliminates the need for bulky cables, connectors, and chassis such as those used in conventional spacecraft. This allows a 75 percent reduction in harness and cable mass, a 50 percent increase in payload fraction, and a 40 percent increase in internal spacecraft volume, thereby simplifying system level integration and test.

Conventional cables and connectors are composed mostly of large, bulky casings that do not serve a direct electrical function for the spacecraft but are required to provide structural support and allow handling during integration and test. MFS eliminates these bulky components and enables the integration of electronic subsystems such as the data transmission and power distribution networks, command and data handling (C&DH) subsystem, thermal management, and load handling. Proprietary Lockheed Martin technologies allow MFSs to be fully reworkable, be less expensive than conventional cabling systems, require much less touch labor, and be much more compatible with envisioned production lines of small, low-cost spacecraft, whether they be one of a kind or of a standardized design.

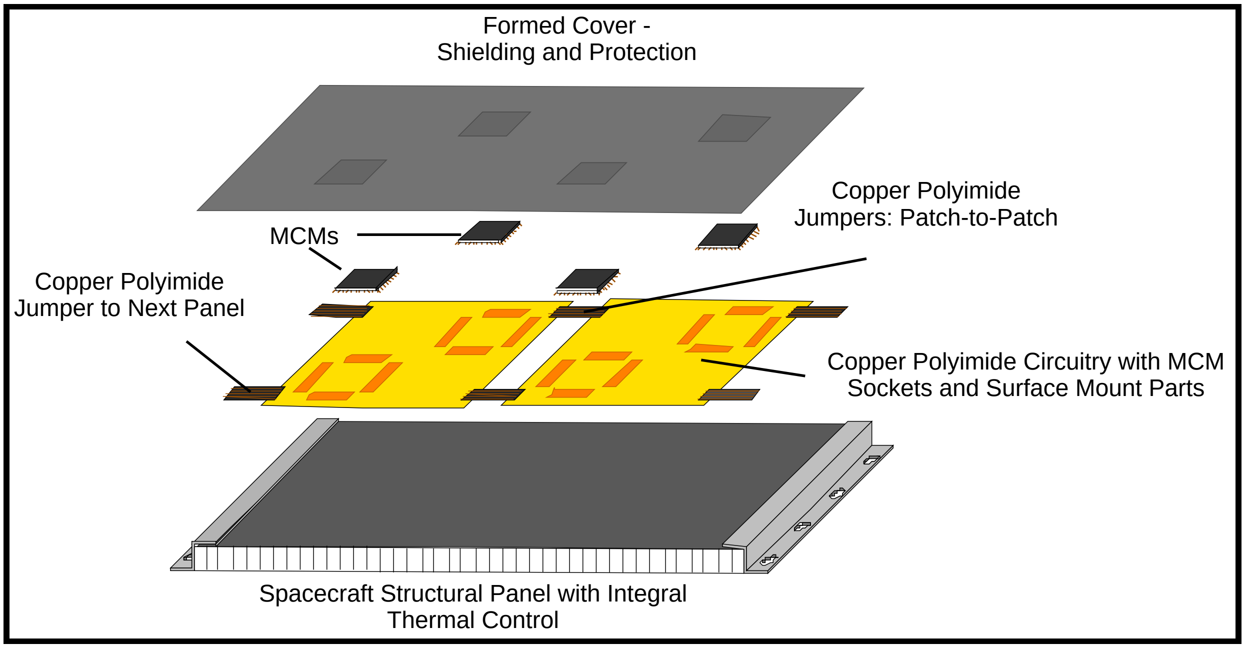

Figure 2 - MFS Panel Including Structural Panel With Integral Thermal Control, Polyimid Flex Circuitry, MCM Sockets, and Formed Cover Providing Electromagnetic Shielding and Protection.

As shown in Figure 2, the data transmission and power distribution network is constructed on thin multi-layer copper/polyimid (Cu/Pl) circuit patches which are bonded onto the structural panel with an adhesive. This intimate contact to the structural surface provides good mechanical performance and enables integral thermal control. Multichip modules (MCMs) are mounted directly on the structural panel via an interface patch. This approach is fully compatible with either two-dimensional MCMs or with the three-dimensional packaging being developed by NMP's Microelectronics IPDT.[10] The circuit patch virtually eliminates the need for large enclosures or circuit boards.

The MAMS team proposes to build on significant programs funded by the Department of Defense and internal resources at Lockheed Martin to fly MFS technologies on every New Millennium mission. We are prepared to fly this technology as early as 1997. Because spacecraft designs can include both conventional electronic boxes and MFS panels, we are taking an evolutionary path with this technology. On DS-1 we have a modest experiment in which test circuits will be built on a MFS and flown to evaluate in flight performance. Our DS-1 MFS work has progressed beyond the preliminary design stage and is well into detailed design. Laboratory model hardware has successfully passed both thermal and vibration tests. We will take another step in validating MFS technology on DS-2 and plan to utilize MFSs to enable a completely cableless system on DS-3 and all NASA space science missions of the 21st century.[11,12]

ADVANCED FORMS OF SILICON CARBIDE

Silicon carbide's extraordinary inherent thermal stability (>35 times better than ultra-low expansion glasses) has been exploited for many years in the manufacture of water-cooled, high-energy laser mirrors. Only recently has the beryllium-like specific stiffness (within 6 percent) of the bulk material been applied to the advancement of lightweight instrument technologies. Development of more durable, less ceramic forms has permitted the optical engineering, process optimization, and implementation of ultra-lightweight instrument concepts like the Planetary Integrated Camera Spectrometer, which are nearly immune to the hostile thermal environment of near Earth and deep space.[13] For example, hundredth of a visible wave thermal stability over a nearly 150K excursion has been demonstrated.

The potential for a quantum leap in low-mass spacecraft technology has been made available by the further development of a mono-material composite form of silicon carbide. This commercially produced form offers reduced mass and CTE (coefficient-of-thermal expansion) compatibility with the bulk optical form used in advanced instruments. In addition, the composite form is robust and machinable. Preliminary measurements suggest that it possesses damping characteristics 4-10 times better than the equivalently configured metal or graphite epoxy.[14] Although these measurements are very intriguing, they have not yet been independently verified. The MAMS IPDT leadership is therefore attempting to arrange tests which can verify this performance as soon as possible.

The unique combination of features found in composite SiC may enable the vision of using a spacecraft bus as the optical bench for remote sensing instruments (cameras, spectrometers, imaging spectrometers, etc.) and for optical communications systems, as depicted in Figure 3. This sensorcraft concept offers a 2-10X savings in mass via superior material properties and the elimination of components in the form of redundant structures and interfaces. Utilizing the results of a parallel, on-going advance in optical communications technology, the functions of spacecraft bus, communications transmit, communications receive, and remote sensing can be combined into one highly integrated, ultra-lightweight package. The New Millennium Program offers the opportunity to realize and flight qualify this vision in a series of steps demonstrating structural interface, optical bench, and complete spacecraft functionality.

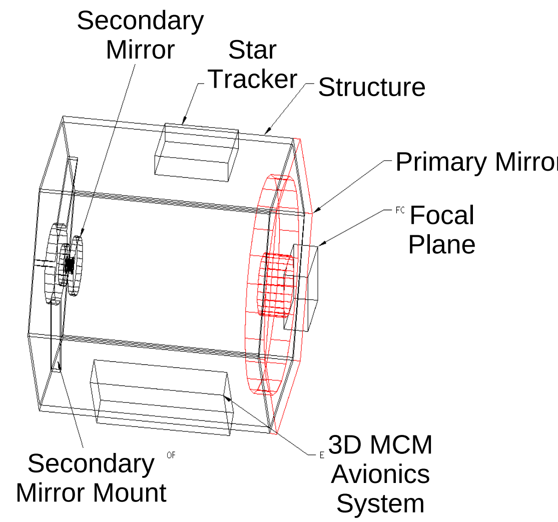

Figure 3 - The sensorcraft concept fully exploits the unique features of advanced SiC materials in an integrated systems design to capture a factor of 2-10 reduction in overall flight system mass.

PRECISION DEPLOYABLE STRUCTURES

Perhaps the greatest technical challenge for packaging science instruments into small spacecraft is deploying large optics on orbit. No amount of improvement in focal plane instrument sensitivity can overcome the limiting resolution of small apertures. This is especially true for missions such as Earth resource mapping, in which the resolution can determine the scientific and commercial value of the measurements.

Recent advances in precision deployable structures technologies will lead to a revolutionary new capability for mechanically deploying large aperture optics from compact packages. Through advances in precision mechanisms, lightweight actuators and latches, ground test, analysis and qualification methods, and lightweight optical mirrors, this technology will advance the state-of-the-practice by several orders-of-magnitude. In comparison with Hubble-era technology, this technology is 50 times lighter and several hundred times less expensive.[15]

Figure 4 is a depiction of a typical precision deployable structure. Key to the low cost and high performance of this technology is its compatibility with conceptually simple mechanisms in conjunction with advanced, low CTE materials such as SiC and low-mass optics.

Particularly important recent advances include:

- Low-mass, sub-micron hysteretic hinge mechanisms with less than 0.5 in-oz of friction
- Lightweight composite mirror panels with IR diffraction limited precision and areal masses of 5 kg/m^2
- New ground test and modeling methods which can predict the on-orbit deployed shape to within approximately a micron
- New kinematically simple deployment concepts for deploying lightweight but mechanically stiff metering trusses, booms, and backplanes
- Lightweight advanced actuators and latches using paraffin and shape memory alloy
- New low CTE materials such as silicon carbide

The benefits of validating this technology on NMP will extend to many aggressive science missions of the 21st century. Applications include advanced LIDAR instruments, high-frequency (≥100 GHz) atmospheric sounding, and deployed components for deep space interferometers. Other missions enabled by this technology include: deep IR galaxy imaging telescopes; extreme UV spectrograph telescopes; next generation X-ray telescopes; sparse aperture Earth imagers; and advanced soil moisture radiometers. Deploying large optics from small spacecraft is critical to 21st century science missions, but the perceived risk in the absence of flight validation prevents their consideration. By validating this technology, NMP will directly enable science missions otherwise inconceivable.

PRECISION INFLATABLES

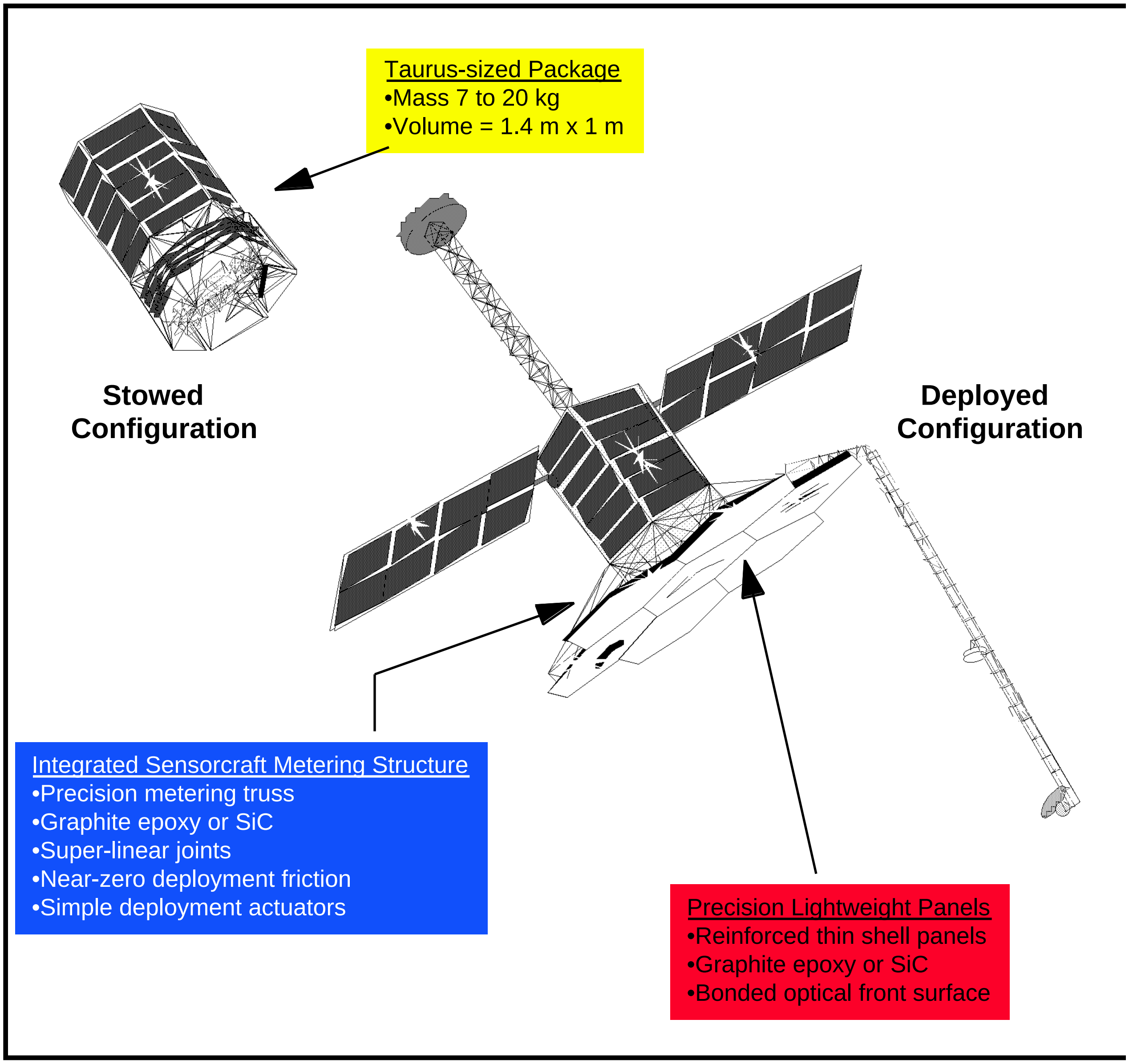

Figure 4 - MAMS Precision Deployable Structures Enable a Hubble-Class Aperture to be Deployed From a Package Compatible With a Small Launch Vehicle

The term "precision inflatable space structures" connotes ultra-lightweight closed-surface structures with millimeter to submillimeter RMS surface accuracies which can take shape in space through controlled inflation. These structures include military space targets in a variety of shapes and cylindrical deployment-and-support booms for instruments, solar arrays, sun shades, or gravity gradient stabilization. In addition, lenticular structures can be built to form solar concentrators and antennas for communications systems, radars, or radio-telescopes.

These structures achieve ultra low mass through the use of a combination of state-of-the-art, commercially available structural films (e.g., polyimids and polyesters) and specifically configured thin-film laminates. In-short duration applications the structure can be designed to stay inflated for the entirety of the mission. In long-duration missions they are inflated, then rigidified in space using one of several physical or chemical processes. High precision is achieved by cutting the structural films or laminates in gores of predetermined shapes to form the proper surface of revolution at the design pressure. Gore shape determination involves highly specialized finite element methods that treat the non-linearities present in the materials properties and the unique mathematical challenge of determining the shape of a film which is loaded in two dimensions and unconstrained in out of plane motion.

The advantages of precision inflatable space structures are very relevant to the goals and objectives of the NMP: They can be a factor of 2 to 5 times lighter, occupy a stowage volume at least 10 times smaller, and (as in the case of large-diameter antennas) cost one to two orders of magnitude less to fabricate than their mechanical counterparts.[16] The small packaging volume and mass can sometimes provide a very significant cost savings because it can enable a reduction in the required launch vehicle size. Another extremely important advantage is high deployment reliability, which is possible because deployment typically depends on the proper functioning of a single solenoid valve which can be placed in a parallel redundant configuration. This high inherent reliability of inflation systems explains why most terrestrial systems requiring high functional reliability (such as life-vests, life-boats and airplane escape systems, for instance) are also inflatable.

Great progress has been made in the last 30 years (see Figure 5) since the inflatable Echo satellite series was launched by NASA.[16,17] There have been over 100 inflatable objects flown by L'Garde, Inc. in several short-duration DoD missions. Through these missions L'Garde has gathered and analyzed a large quantity of data on the design, test, fabrication, handling, packaging, deployment, thermal, and dynamic behavior of inflatable structures. In the case of precision inflatable reflectors, ground test systems have been built and measured for surface accuracy and, recently, a 3-meter-diameter ground test unit gave surface accuracies of 0.67 mm RMS, extending the technology into the Ka frequency band. Two years ago the first inflatable solar array structure was successfully deployed by inflation and tested in the Naval Research Laboratory thermal vacuum chamber.[17]

In May 1996 a collaborative effort between L'Garde, JPL, and NASA will culminate in the deployment and flight of a 14 meter diameter inflatable reflector (known as the Inflatable Antenna Experiment) on board STS-77 (see schematic included in Figure 5).[17,18] The flight will demonstrate successful deployment of this large reflector and will measure several parameters of interest including on-orbit surface accuracy vs. thermal loading in various sunlight conditions.

For the NMP, the MAMS team proposes that L'Garde collaborate with JPL, other NASA centers, and the USAF Phillips laboratory to fly several inflatable structures validation experiments:

- low-cost piggy-back experiments to demonstrate the deployment accuracy and on orbit characteristics of simple structures such as booms and sun shades,
- ultra-lightweight operational antennas in the X-band and possibly higher frequencies for telecommunications, synthetic aperture radar, or passive soil radiometry, [19,2-]
- advanced inflatable solar arrays, and eventually
- the dual use reflector (for communications and power) known as the "Power Antenna."

The latter, if its development and flight prove successful, could eventually replace nuclear sources as the power system of choice for deep space missions.[21] The flight of these systems will be the most important step towards the acceptance and widespread use by the space community of these truly revolutionary and highly efficient structures.

Power Antenna feasibility has been shown in a NASA Phase 1 SBIR.[21] A recently initiated Phase 2 SBIR follow-on will address minimization of reflector pressure in RF and solar concentration ground tests. This, along with strong leveraging from other inflatable antenna programs, will further reduce the insolation level at which Power Antennas can function to the 3-5 W/m^2 level making it possible to consider all solar missions to the outer solar system. The MAMS team is collectively working to identify technology development funds to complete a full-up ground test of the Power Antenna circa 1998-1999. A flight test unit could be available for a New Millennium technology validation flight circa 2000-2001. If successful, this flight will open the door to all solar powered missions to the outer solar system in the 21st century.

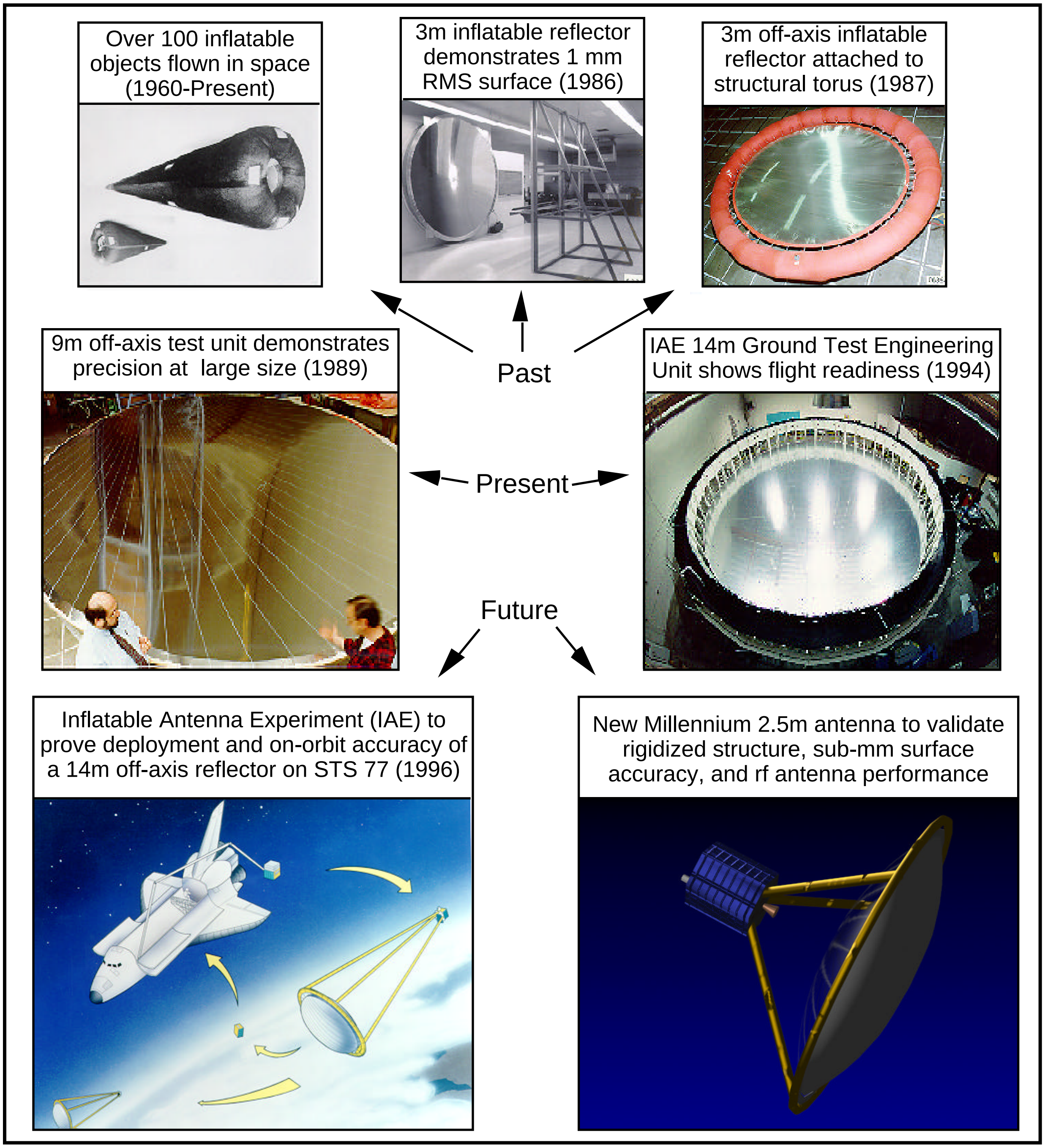

Figure 5 - The Past, Present, and Near Future of Precision Inflatable Structures

IV. BREAKTHROUGHS IN PROPULSION AND POWER

Propulsion and power are two of the most important keys to cost-effective space science missions. These two subsystems together comprise over 65 percent of the mass and 30 percent of the cost of a typical deep space orbiter type spacecraft.[8] The problems of propulsion and power will become even more acute in the new millennium as deep space missions are asked to go farther from the Sun and get to their destinations faster.

In the area of propulsion, the MAMS team is working with its member from the Olin Aerospace Company (OAC) to pursue two technologies with promise for New Millennium mission architectures: the COMPact Hydrazine Propulsion System (COMP) and miniature Pulsed Plasma Thruster (PPT) systems. Both of these technologies are modular and easy to integrate onto a variety of spacecraft bus designs. Both also offer the capability of being delivered and integrated into the spacecraft fully loaded. Beyond these systems the MAMS team is planning validation activities for advanced Solar Electric Propulsion (SEP) systems that build upon the success of the NASA SEP Technology Application Readiness (NSTAR) Project which will

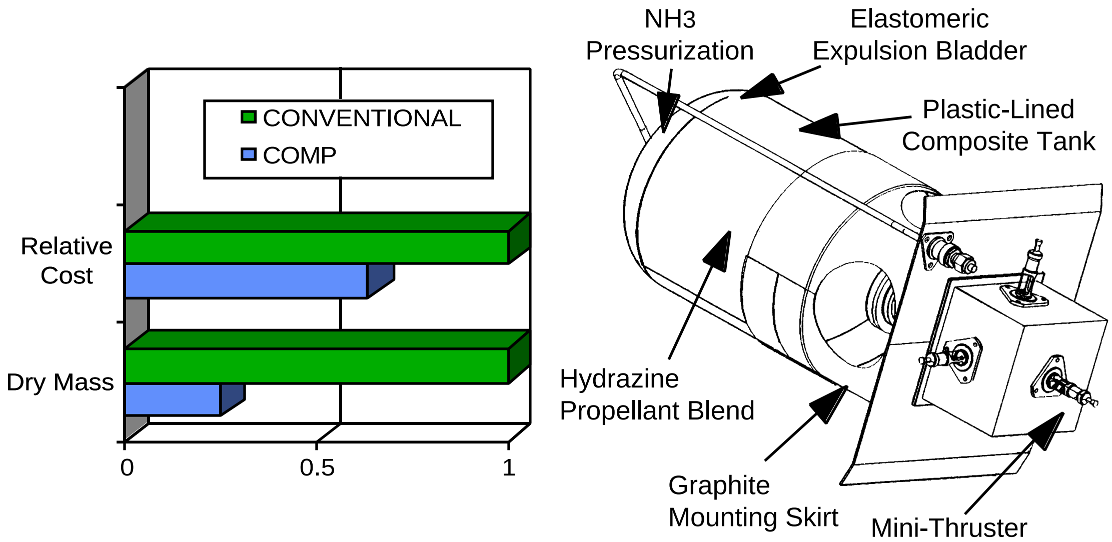

Figure 6 - COMP Propulsion System Benefits and Schematic

flight validate solar electric ion propulsion on DS-1 to provide even shorter trip times, reduced launch vehicle requirements, and higher payload fractions.[4]

COMP

The COMP system is an outgrowth of OAC internal research and development focused on reducing the cost and weight of hydrazine system components. It offers a totally self-contained hydrazine propulsion system capable of 25,000 N-s of total impulse. As shown in Figure 6, the system uses flight-proven OAC 0.889 N thrusters in a three unit rocket engine module. The envelope of the system is designed to be compatible with small spacecraft designs. Tank size will vary with mission requirements, but the typical size for the 25,000 N-s system is 60 cm in length by 20 cm in diameter. Two of these modules provide total three-axis control for small spacecraft ACS.

The COMP system can also be configured to provide main propulsion for small spacecraft. Because it is designed to be fully self-contained, the interfaces with the spacecraft are minimized. The system also offers the advantage of having an extremely low recurring cost once the basic configuration has been established. In quantities of 10 or more, costs are anticipated to be approximately $150,000 for the complete dry system. COMP is designed to be fueled at the factory and delivered to the customer fully fueled, ready to be mounted and integrated into the spacecraft for launch. This can also enable a significant operational cost and schedule savings.

THE PULSED PLASMA THRUSTER

The Pulsed Plasma Thruster (PPT) system is another answer to NMP mission needs for small, low-cost propulsion systems. Like the COMP, it is also fully self-contained and requires only a minimum of interfaces with the spacecraft. The PPT is an electric propulsion device utilizing the interaction of a current and self-induced magnetic field to ablate, ionize, and accelerate solid Teflon fuel. The Teflon undergoes phase changes into gas and then plasma as it is ablated, a few monolayers at a time. The constituents of the plasma are ionized and accelerated by the energy present in the electrical discharge. The energy required is stored within the PPT system in an energy storage capacitor, which is charged by any 28 volt unregulated DC bus capable of providing a few tens of watts.

Figure 7 shows a schematic of the PPT system and a model of the miniature PPT system. The system is inherently simple and reliable in part because it has only one moving part, the fuel bar, which is fed with a spring into the breech of the discharge chamber. The principal challenges being addressed in NASA-funded technology development are reducing the system mass dramatically and improving the thrust efficiency of the PPT. Within the framework of the MAMS team and the NMP architecture, the PPT offers a candidate for a truly miniature thruster system capable of meeting the propulsion requirements of a 21st century nano-spacecraft.

The chief technical benefits of the PPT relative to chemical thrusters are its increased specific impulse (1000-1500 s) and reduced minimum impulse bit (100-500 μN•s).[22] This minimum impulse bit is two orders of magnitude less then that of chemical propulsion systems and it promises to revolutionize our approach to precision station keeping and fine scale attitude control. For example, a PPT with a 200 µN•s minimum impulse bit could easily provide control for precision station keeping of a constellation of 200 kg spacecraft to the 100 µm level. This is in contrast to the 1 cm level of control typically assumed in NASA studies of advanced interferometer constellations.

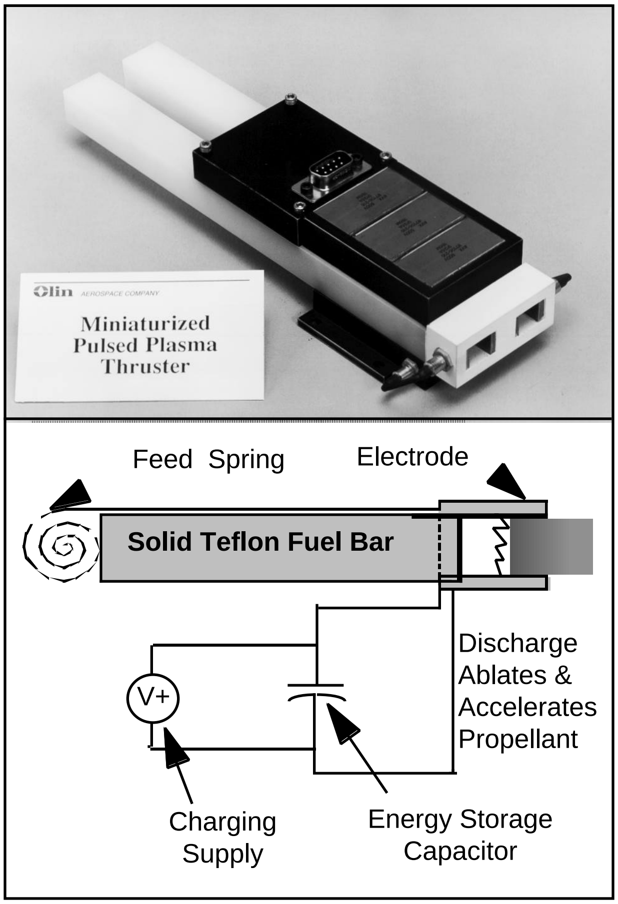

Figure 7 - The Pulsed Plasma Thruster, Schematic Diagram and Model

Because the PPT is truly enabling to the NASA vision of constellations of microspacecraft forming 21st century interferometers that can provide multi-pixel images of Earth-like planets in nearby solar systems, the MAMS IPDT intends to flight validate advanced PPT thruster technology on New Millennium missions. First we plan to conduct a piggy back flight of this technology on an Air Force technology demonstration satellite in 1998 to validate the low contamination of optical surfaces we expect from this device. We then intend to provide a full suite of PPTs to the DS-3 flight team as the primary station keeping and attitude control thruster system for DS-3. This will provide DS-3 with significantly enhanced performance and the opportunity to fully validate a technology that enables the NASA vision of 21st century interferometer missions.

OTHER ADVANCED PROPULSION TECHNOLOGIES

We believe that SEP is the key to rapid, low-cost access of space science spacecraft to the entire solar system. The first step to fulfilling the New Millennium vision in this area is the flight validation of the NASA SEP Technology Application Readiness (NSTAR) ion propulsion system on DS-1. However, NSTAR represents not an end, but a beginning of the age of electric drives for rapid exploration of the solar system. Our long-range road map for electric propulsion technology envisions significant advancements beyond NSTAR for SEP. Particularly important steps on our long-range SEP road map include:

- High-performance ion engines capitalizing on slotted 3-grid carbon-carbon grid technology,[23,24]
- High specific impulse, long-life plasma engines,[25,26]
- Direct-drive SEP systems in which high-voltage solar arrays are linked directly to plasma engines or advanced ion engines using state-of-the-art switching technology to eliminate electric propulsion power processors, and
- Miniaturized, modular electric propulsion systems that are compatible with microspacecraft of any size.[25]

Of these advancements, the greatest performance leap is that offered by direct-drive systems, which have the promise of delivering spacecraft to the outer solar system with trip times of 5 to 7 years using Med-Lite class launch vehicles. The concept of direct-drive SEP based on advanced plasma engines was originally proposed 25 years ago[26] but was largely forgotten or ignored until 1994, when JPL reintroduced the concept in a proposal to the Department of Defense Space Experiments Review Board[27] and more recently studied by NASA LeRC.[28] The concept has stimulated increasing interest from various potential users.[29]

A direct-drive discharge supply has been tested in the laboratory at JPL. In the JPL demonstration, which was funded by internal discretionary resources, a direct drive power switching unit (PSU) drove a D-55 thruster with anode layer (TAL) at 300 V and 4.5 A. A commercially available 10-kW D.C. power supply provided power to the PSU, provided "smart" thruster turn-on and shutdown. The system performed flawlessly and the PSU performed at an efficiency of 99%. At the beginning of CY 1996 JPL will perform additional testing to increase the direct-drive PCU power and shut-down capabilities and plans to test the PSU on a solar simulator.

THE SCARLET SOLAR ARRAY

All New Millennium missions share one common element —the need for power. Most of the missions, including DS-1, will use solar arrays as power sources. The array mass and cost is especially important for the first deep space mission because it uses electric propulsion that needs large panels producing many kilowatts.

BMDO will develop a 2.6 kW SCARLET type array system for the NMP first deep space mission.[30] The Solar Concentrator Array with Refractive Linear Element Technology (SCARLET) is a new technology that holds promise for halving the recurring array cost while decreasing the array mass by 50 percent and size by 30 percent. In addition, the array is well suited to high radiation missions because it can be made very radiation hard without incurring a large mass penalty.

The linear concentrator array takes advantage of technologies working in tandem: flexible Fresnel lens, dual junction cells, and low-mass structure. Concentrator technology allows arrays to have much lower cell area for a given power level. The configuration of the SCARLET lens system is depicted in Figure 8.

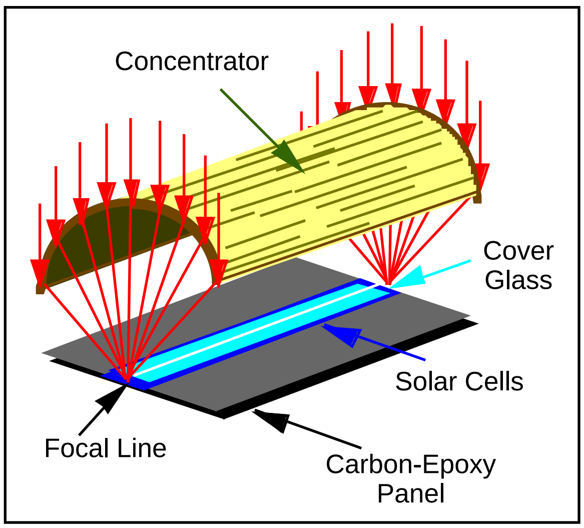

Figure 8 - SCARLET is based on linear convex Fresnel concentrators that reduce cell area by more than an order of magnitude.

Because array costs are traditionally dominated by cell costs, the availability of array systems which use only 1/10th of the cell area of a comparably sized planar (full-area) array can reduce the cost for 21st century missions by a factor of two. The SCARLET array can provide mass savings depending on the severity of the mission's radiation environment because high-radiation protection is necessarily very massive and a much smaller cell area means a smaller area to protect. This feature is of greatest value in high-radiation, Van Allen belt-flying missions, such as electric propulsion orbit raising.

The SCARLET technology also enables more cost-effective employment of new high-efficiency solar cells such as 22 percent efficient GaInP2/GaAs/Ge cells. Since these cells will be relatively expensive, at least in the near term, the cost benefit derived by reducing cell area is more critical. Additionally, the SCARLET technology can be used to mitigate the debilitating effects of interplanetary distances on solar cell efficiency. In standard arrays these *LILT* (Low Intensity, Low Temperature) effects increase the size and hence, cost of a solar array for a multi-AU (Mars and beyond) spacecraft.

The team developing the array consists of BMDO, AEC Able, Entech, ASEC, NASA LeRC and JPL. We believe that the low cost and high performance of the SCARLET array will draw many users among early 21st century scientific and commercial mission managers.

LITHIUM ION BATTERY

Rechargeable lithium batteries offer significant performance and cost advantages compared to Ni-Cd and Ni-H2 batteries and will enable the required miniaturization of energy storage subsystem for NM. The performance advantages include higher specific energy, energy density, cell voltage, coulombic and energy efficiency, low self-discharge rate, and lower battery costs compared to the SOA Ni-Cd and Ni-H2 batteries. These advantages translate into several benefits including reduced mass and volume of the energy storage subsystem, improved reliability, extended mission life, and lower power system life cycle costs.

Lithium ion batteries have 2-4 times higher specific energy (Wh/kg) and energy density (Wh/l) than the SOA advanced versions of the nickel-cadmium (Ni-Cd) and nickel-hydrogen (Ni-H2) batteries presently being used in various satellites. Further, Li ion batteries have two times the specific energy of the SOA Ni-MH batteries. These cells have significantly higher cell voltage and therefore typically require only one third as many cells per battery as state-of-the-art systems. For example, some of the lithium cells deliver 4.1 volts/cell or over three times the voltage of Ni-Cd cells of 1.2 volts/cell. On this basis, a 28-volt battery system will require only 8 lithium cells compared with 22 cells for a Ni-Cd battery. In addition, lithium cells have significantly higher coulombic and energy efficiency compared to SOA batteries. Higher energy efficiency of these batteries will enable reduction of the solar array size. Lithium ion cells also exhibit much lower self discharge compared to state-of-the-art batteries.

Lithium batteries represent savings to space missions. The savings are associated with: a) lower battery cost, and b) lower launch costs. It is projected that lithium batteries will cost significantly less than Ni-Cd and Ni-H2 batteries due to use of low-cost materials and simpler manufacturing processes. Since up to 50 percent of mission cost can be for the launch vehicle, reduction of spacecraft mass and volume (resulting from the use of lithium batteries) can therefore significantly lower the overall mission cost.

The first deep space mission of the NMP will use two Li-ion batteries with the following parameters:

Voltage:	28±5 V
Capacity:	10 Ah
Cycle Life:	> 1000 cycles
Operating Temperature:	0 - 30 °C
Operational Life:	> 10 years
Specific Energy (Wh/Kg):	> 100
Energy Density (Wh/l):	> 160
Mass (kg)	> 3.1

The team developing the batteries consists of Yardney Technical Products, Wright Laboratory and JPL.[31]

V. PLANETARY SURFACE INTERFACE

Sample returns have been the Holy Grail of planetary exploration because they permit very high-precision measurements to be made with a multitude of complex laboratory instruments. Because of the high cost, no sample return missions have been conducted except for the Apollo missions to the Moon. The Penetrator Sample Acquisition System (PSAS) is a low-cost technology that will open a new era in planetary exploration.

Sample acquisition by means of ballistic penetration affords the opportunity to significantly reduce mass and complexity compared to an independent, autonomous surface lander. By contrast, a penetrator is a simple ballistic device with mechanical designs that permit sample acquisition and release for return to Earth. The penetrator deployment and sample retrieval schemes depend on the type of body to be sampled. As shown in Figure 9, for a small, low-gravity body with no atmosphere, e.g., a comet or an asteroid, a spinning penetrator can be deployed at close range and retrieved via a tether. For a large body with an atmosphere, like Mars, penetrators could be dropped from a lander that carries the return vehicle and a rover. The rover could collect the subsurface samples from the penetrator and surface samples then deliver both types of samples to the return vehicle.

For a small body, the use of a penetrator to collect samples allows the elimination of the lander and a complex sample acquisition and return system. Thus, a significant savings in mass, spacecraft complexity and size, and propulsion system requirements will result. In the case of Mars, a lander and return-to-orbit vehicle is still required, so the gains are less. What is added in this case is the ability to collect deep sub-surface samples without the requirement to land large, power-intensive drilling mechanisms.

The penetrator concept eliminates the need for an independent, capable lander and the complex, autonomous maneuvers associated with sample retrieval from the surface to the spacecraft. It will permit the collection of multiple samples from the target body at remotely separated sites with little added mass compared to the multiple lander alternative. It significantly reduces the mass and complexity of returning samples to Earth.

In addition to simplified technical requirements, significant reductions in total system cost will result from smaller launch vehicles and reduced lift mass. Synergistic design of a small spacecraft with an integral deployment reel will optimize system volume and mass requirements. Tether spacecraft technology with an integral sampling device represents a revolutionary technical advance. The concept lends itself to sampling multiple sites as well by having

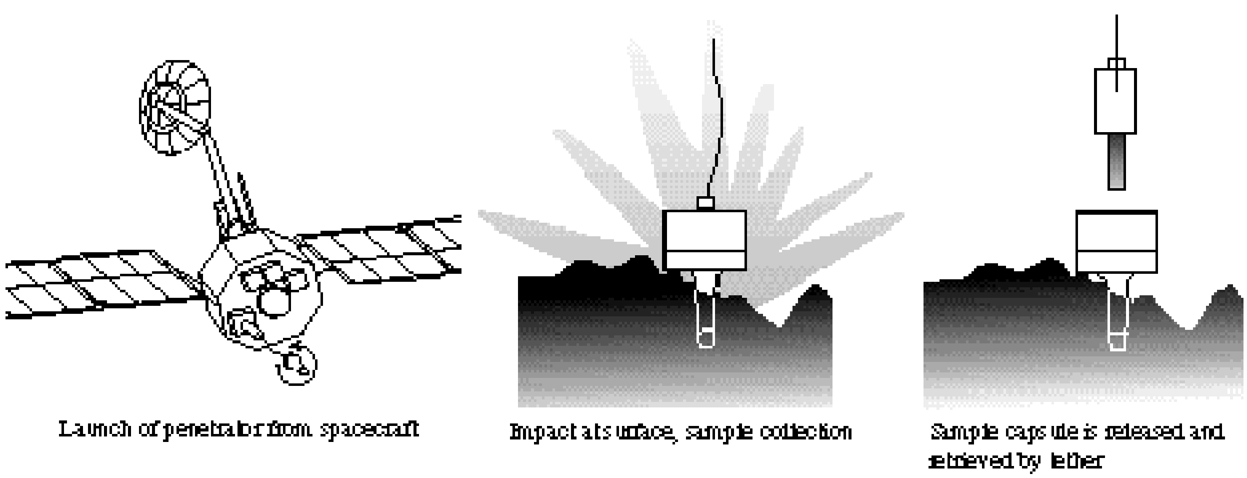

Figure 9 - Penetrator Sample Acquisition and Return As It Could Be Applied to Comet Sample Return

multiple penetrator bodies with a single tether and reel mechanism. With little added mass and complexity the penetrator can host a variety of instruments for in situ measurement. For example, the acceleration of penetration can be measured and reported to establish the material properties (penetrability) of the surface.

The functionality of a hollow core penetrator is not limited to retrieving the sample capsule via a tether. Technology advances in docking maneuvers could create a scenario where a spacecraft would orbit a body, determine the optimal impact site, launch the penetrator without a tether, receive data from the penetrator's instrumentation while orbiting the body for some period of time, then dock and retrieve the sample capsule. Technology advances in miniature in situ instrumentation could be demonstrated on the first flight if desired.

The application of PSAS to Mars allows a small, simple device to collect deep samples and deliver them to the surface without the need of any energy source. The penetrator is completely inert; it has no power source, guidance system, or transmitter. The penetrator falls a few tens of meters up-range from the landing site of the return vehicle and is easily found by the rover. The samples are packaged by the penetrator and ejected onto the surface by a spring-loaded mechanism that is triggered by the release of the high g loads from the impact.

The NMP does not presently include a mission in which a rendezvous with a small body would allow the demonstration of PSAS technology and for that reason PSAS is not presently in the NMP plan. However, ground based tests conducted by the University of Arizona this summer have shown the technical feasibility of PSAS. The MAMS team intends that the technical results of these tests and the important implications of these technologies will motivate NASA to initiate a significant technology program in planetary surface interface systems. With such a program in place it could be possible for low-cost, Discovery-class, missions to accomplish important in situ science and sample return missions.

VI. PROCESS MILLENNIA

Part of the NMP vision is to create and validate a seamless process for the conception, design, development, test and operation of the real space missions of the next millennium. This combination of improved process, computer aided environment and state-of-the-art tools is called Process Millennia.

Although Process Millennia applies to all of the NMP IPDTs, organizationally the Process Millennia effort is being lead by the MAMS IPDT. MAMS will attempt to create Process Millennia in part through specific activities that will be directed toward addressing problems identified by the NMP flight teams. Figure 10 shows how NMP will use its deep space missions to infuse Process Millennia into NASA space science programs.

When complete, Process Millennia will begin by engaging the customer in defining acceptable ranges of product performance, cost, and risk. The system and team will then be architected to minimize total life-cycle cost. Design, manufacturing, and test will be carried out concurrently in an environment which allows instant shared access to all program information. Advanced computer-aided tools, standards, and best practice will be used. Nearly autonomous operation of the spacecraft will follow.[32]

Process Millennia will reduce cost in a number of ways. System and team architecture will be chosen with a more complete understanding of program performance, cost, and risk. Engineers will design with a knowledge of cost. The process will be more efficient, with more easily shared information and smaller teams leading to higher quality products. The process will be faster, using standardized practices and products.

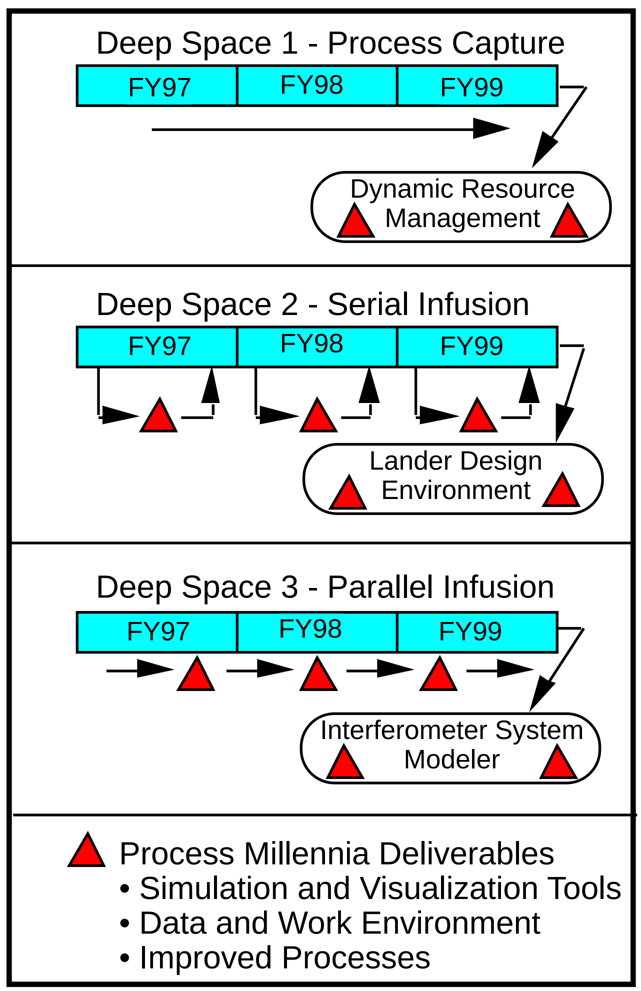

Figure 10 - Process Millennia Infusion Into NMP Deep Space Missions

A useful analogy can be drawn between the creation of a the real spacecraft of the next millennium and the preparation of a meal by a professional chef. Much of the NMP focuses on developing better meat and potatoes (the new technologies) in order to make the meal better. But like a good meal, the real cost is not in the foodstuff, but in the labor. To make a meal faster, cheaper, and better, the entire effort must be examined. Chefs cook in a kitchen (the environment) using appliances (the tools) according to techniques and recipes (the process). A well laid out kitchen can make the job for the team of cooks easier, and the invention of a new appliance, the microwave, allows much faster cooking than previously thought possible.

Not only does a good recipe make a better meal, but from the system perspective buying the foodstuffs (supplier relations), making the menu (customer requirements), and ensuring that all dishes arrive hot on the table at the right time (concurrent just in time manufacturing) are all important and labor-intensive parts of the process. The cost and speed of a meal prepared in the kitchen can range widely from that of fast food (highly modularized) to a slow, expensive but fine French meal (highly customized). Trying to improve the cost of a meal without examining process, environment, and tools would be foolhardy. We recommend a similar examination of the design/build process, environment, and tools set for spacecraft.

The potential for large cost savings with implementation of Process Millennia is widely recognized and numerous activities are underway to address the different aspects described above. An NMP-sponsored Workshop was held to identify on-going activities and their interrelations with each other. The NMP approach is to build on this existing foundation. NMP plans to implement cost-saving procedures in a step-by-step manner while simultaneously improving the computer-aided environment and associated tools.

For each of these deep space missions a Process Millennia team will be assembled which will function in a manner parallel to the flight team. This Process Millennia team will include JPL, university, and industry members who are technologists, engineers, or designers in some subset of the areas of information systems, autonomy, systems engineering, mechanical engineering, computer-aided design, and all the major spacecraft science and subsystem disciplines. The Multidisciplinary Integrated Design Assistant for Spacecraft (MIDAS) will be an important aspect of our Process Millennia work with the deep space teams.

For DS-1, this team's job will be to shadow the work of the flight team to capture the end-to-end design and development process. The product of their work will be the software, hardware, and processes needed to conduct future mission design and development activities using dynamic resource management. Dynamic resource management is a relatively new concept for the spacecraft development community in which margins and flight system resources are managed dynamically instead of using the traditional system of allocating resources to subsystems and monitoring reserves and contingencies.

In DS-2 the Process Millennia team will work more directly with the flight team to develop design tools in parallel with flight system development. As these tools become useful they will be infused directly into the flight team's design process. The goal of the team will be to develop, by the end of the DS-2 design development phase, an integrated lander design environment that will be generic enough to be used on all future Mars lander missions. The application of advanced probabilistic methods will be an important and critical element of the Process Millennia work with DS-2.

Finally, in DS-3 we hope to commingle the Process Millennia team directly with the flight team to accomplish serial infusion of tools and design environments. The final goal of the work with DS-3 will be the development of an Interferometer Design Tool that will allow future designers of interferometers, be they free flying or single spacecraft based, to more easily and less expensively design and analyze their missions.

VII. SUMMARY & CONCLUSIONS

We have described a wide spectrum of complementary advanced MAMS technologies in terms of their major contributions to NASA's 21st century missions. Materials and structures technologies encompass (1) MFS wherein electronics and structures are integrated in a way leading ultimately toward cableless spacecraft, (2) advanced thermally-stable SiC materials for use in optical instruments and support structures that greatly enhance the quality of scientific data, (3) precision deployable structures and mechanisms to permit use of science-enhancing large optics on small spacecraft, and (4) inflatables to provide large apertures for low-cost missions at greatly reduced mass and volume as compared to conventional apertures.

Advanced power and propulsion technologies include (1) systematic activities leading toward development of a Power Antenna concept that uses the inflatables technology to deploy a low-mass dual-purpose aperture that serves as both an antenna and solar concentrator

for power generation, (2) a low-mass compact hydrazine propulsion system that features a fully fueled modular design to greatly reduce unit costs while simplifying integration with the spacecraft, (3) an advanced low-mass Pulsed Plasma Thruster characterized by inherent simplicity and reliability while being packaged as a fully-fueled modular unit for ease of integration, (4) an advanced BMDO-originated solar concentrator array technology, SCARLET, that employs Fresnel concentrators coupled with efficient

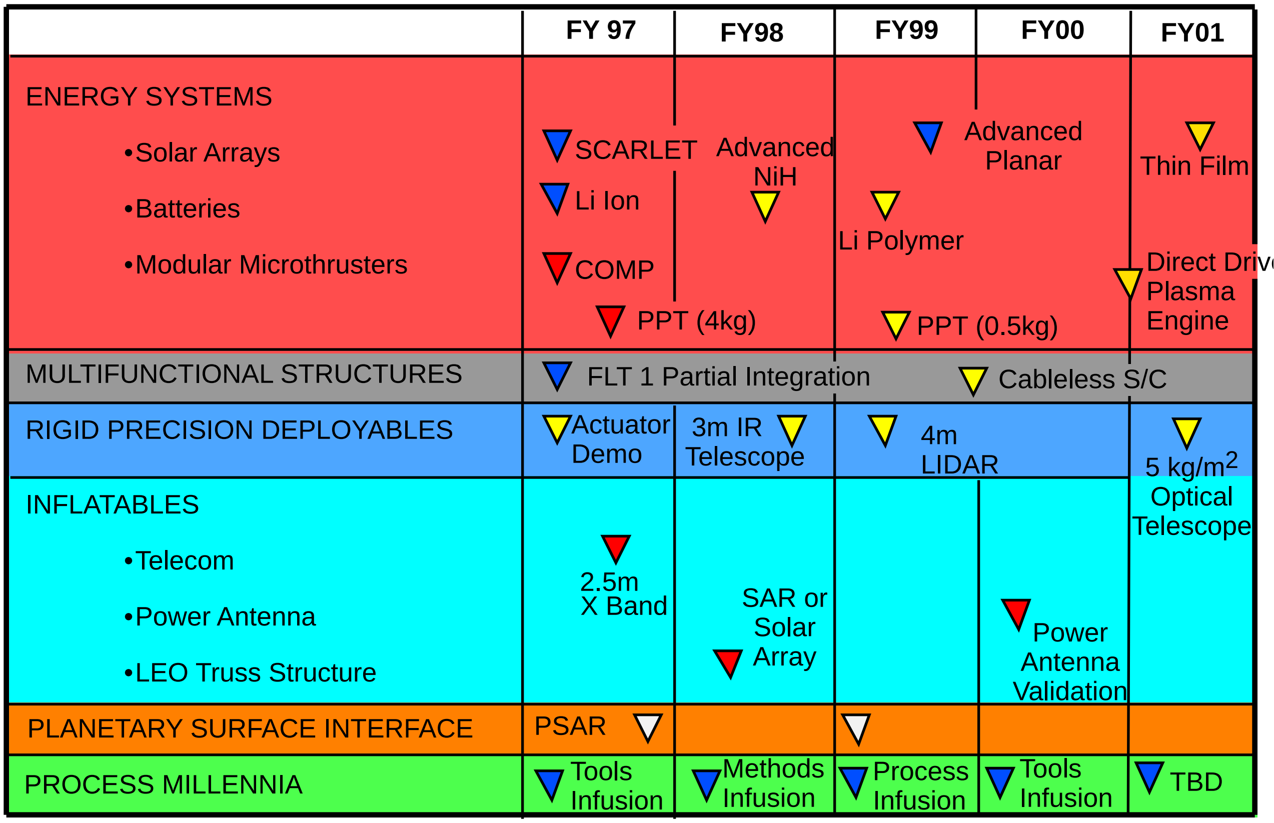

Figure 11 - Simplified Summary of MAMS IPDT Technology Road Map. Dates shown are for technology hardware availability. Earliest launch is typically several months later.

solar cells to reduce the quantity of cost-driving solar cells and a low-mass structural design for the concentrator-cell arrangement that provides major cost and mass savings, and (5) a rechargeable lithium ion battery that enables miniaturization of the energy storage subsystem while providing major reductions in cost and mass.

Activities in Planetary Surface Interface technologies are focused on developing a technology to fill a key capability need for the 21st century, namely an affordable way to achieve sample return missions. A ballistic penetration system technology capable of providing affordable sample return missions is delineated in design embodiments including penetrator-tether return systems for primitive bodies and use of penetrators to generate surface-deposited samples coupled with rover sample collection for planets such as Mars.

The MAMS effort includes the leadership of the NMP-wide Process Millennia activity. Process Millennia embodies improved seamless processes from conception through operation and is implemented through use of computer-aided environments employing state-of-the-art tools. Because of the wide-spread recognition of the very large cost savings that could accrue, numerous private and governmental programs are underway to develop various aspects of Process Millennia. The effort within NMP is focused on coordination of these different activities, standardization to permit spreading the benefits widely, and implementing the process in stages as it evolves.

Figure 11 is a summary of the MAMS IPDT's road map for the technologies discussed in this paper. Each triangular milestone mark in Figure 11 represents a recommended technology validation flight of a technology this team has identified, studied, and ranked highly. For each milestone on this chart, the MAMS team evaluated ten to twenty alternative technologies and rejected them on technical grounds. The status of each of these flight validation activities is noted with a color scheme. Blue triangles represent flight validations that are presently funded and in work. Yellow triangles represent activities that are not yet funded but which we believe have a good prospect of being funded and validated on a New Millennium flight. Red triangles are those technology demonstrations that have been passed over by New Millennium flight selections based on risk or mission compatibility or are not adequately funded, but which the MAMS team still feels are critical to the success of the NMP. White triangles are special cases not covered by any of these categories.

The achievement of NASA's 21st century vision of employing fleets of small, low-cost, autonomous spacecraft as the basis for affordable missions with large collective science returns requires technology advances across a broad front. Many of these key technologies fall in the MAMS category. The selected prioritized set of technologies the MAMS team is currently pursuing provides a major first-step contribution to NASA's 21st century vision.

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